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TECHNICAL REPORT NO. 1-695

SOME BASIC PRINCIPLES OF SCALING EXPLOSION-PRODUCED DAMAGE TO DEEP UNLINED OPENINGS IN ROCK (U)

by

G. B. Clark

October 1965

Sponsored by

Research and Development Command, U. S. Army

and

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Foreword

(U) This study was undertaken to examine the practicability of modeling the effects of explosions on deep underground protective structures, with special emphasis given to modeling the response of unlined cavities in massive rock formations. The work was sponsored by the Office, Chief of Engineers through the U. S. Army Research and Development Project "Military Engineering Applications of Nuclear Weapons Effects Research." For the most part, the study was completed during the summer of 1964. The information compiled and analyzed in this report was used as a basis for designing a small-scale field test in which a concrete model system was used to simulate the effects of an explosion on unlined cavities mined within a massive homogeneous rock. (U)

(U) This report was prepared by Dr. George B. Clark. The author desires to acknowledge the helpful suggestions of Mr. John N. Strange and Lt. A. J. Hendron, Jr., Chief of the Engineering Research Branch and Military Assistant to the Chief, Nuclear Weapons Effects Division (NWED), respectively. The study was accomplished under the overall supervision of Messrs. F. R. Brown and G. L. Arbuthnot, Chief and Acting Chief of the Nuclear Weapons Effects Division, respectively. (U)

(U) Col. Alex G. Sutton, Jr., CE, and Col. John R. Oswalt, Jr., CE., were Directors of the Waterways Experiment Station during the preparation and publication of this report. Mr. J. B. Tiffany was Technical Director. (U)

Contents

Glossary

c	Sonic velocity, ft/sec
d	Depth, ft
d_c	Closure distance, ft
E	Young's modulus, $lb/in.^2$
G	Shear modulus of elasticity, $lb/in.^2$
k	A constant
L	Length, ft
M	Mass, lb
r_a	Apparent crater radius, ft
R	Range, ft
R_{cd}	Critical range at which crushing ceases, ft
t	Pulse duration, msec
T	Time, sec
v	Particle velocity, ft/sec
V	Apparent crater volume, ft^3
W	Yield of explosive, lb, kt, or Mt
Z	Depth of burst, ft
ϵ	Strain, dimensionless
ϵ_r	Radial strain, dimensionless

[redacted]

ϵ_u	Ultimate strain, dimensionless
λ	Model-to-prototype length ratio, dimensionless; also Lame's constant (equation 2)
λ_c	Scaled depth of burial of charge, $ft/lb^{1/3}$ or $ft/kt^{1/3}$
λ_r	Scaled range, $ft/lb^{1/3}$ or $ft/kt^{1/3}$
μ	Model-to-prototype mass ratio, dimensionless
ρ	Mass per unit volume (mass density), lb/ft^3
σ_r	Rupture stress, $lb/in.^2$
τ	Model-to-prototype time ratio, dimensionless

Summary

(U) An analysis is presented of the scaling parameters which are important in scaling explosive-induced waves in earth materials and the effect of these waves on deep underground structures. Basically, two approaches to scaling are possible. Gravitational effects can be allowed for and material properties scaled, or gravitational effects can be ignored and material properties kept the same in the model as in the prototype. The study indicates that peak strain is dependent upon yield as well as other factors. Closure distances resulting from confined detonations vary from 1.85 to 2.00 ft/lb$^{1/3}$, the variation apparently being due to properties of rock. The strain magnitude times the strain pulse period together with the energy level of the pulse appear to be reliable parameters for damage prediction. High explosives (HE) and nuclear explosives (NE) are believed to be almost equal in effect for depths of burial greater than λ_c = 0.20 ft/lb$^{1/3}$; for shallower burial, an equivalence factor must be used. (U)

(U) The foregoing analysis indicates that model scaling can be used to advantage to investigate a number of the factors which are important in the response of deep underground structures to explosive attack. (U)

SOME BASIC PRINCIPLES OF SCALING EXPLOSION-PRODUCED DAMAGE TO DEEP UNLINED OPENINGS IN ROCK (U)

Introduction

Objectives

(U) 1. The immediate objective of the study reported herein was to furnish a basic foundation for investigating the feasibility of modeling some of the important parameters affecting damage as caused by surface or near-surface nuclear detonations to deep, unlined protective shelters in rock. The design of model experiments and instrumentation, and the development of standards for evaluating the test results will require considerable innovation. However, it is hoped that model test results will furnish a basis for evaluating quantitatively the effects of such parameters as geologic structure, cavity size and shape, and various liner materials and supports on the overall response of an underground inclusion to explosions in the megaton range. As a first step toward developing a modeling scheme, a detailed analysis was made of related field and laboratory experiments and the data obtained from them. (U)

Background

(U) 2. There are very few model tests of record which deal with the destruction of underground openings by explosives. Jones and McCutchen[1*] conducted tests utilizing black powder and materials with properties scaled according to the laws of similitude, i.e. a gravity ratio of 1 was assumed. McCutchen[2] and Arbuthnot and Strange[3] outlined some of the basic problems involved in modeling properties of materials to fit selected modeling schemes. (U)

(U) 3. Clark and Bruzewski,[4] utilizing natural rock materials and chemical explosives in tunnel demolition model experiments, showed that the cube-root law could be used to predict closure distances for charges in the range of 1.0 to 6.0 lb. Results of the Underground Explosion Test (UET) program, which included charges weighing up to 320,000 lb (TNT),

* Raised numbers refer to similarly numbered items in the Selected Bibliography at the end of this report.

also agreed closely with cube-root scaling for tunnel closure phenomena.[5,6] Several very small scale experiments utilizing only a few ounces of HE have been reported,[7] but the results for the most part are too inconclusive to be applicable. In addition to the HE tests of the UET program, closure distances are now available for several underground, contained nuclear explosions (table 1). Limited strain and particle-velocity measurements were obtained from a few of the experiments listed in table 1.[8] (U)

(C) 4. In general, recent analyses of cratering information indicate that for scaled depths of burial greater than approximately 0.20 ft/lb$^{1/3}$ (~25 ft/kt$^{1/3}$), the cratering effectiveness of nuclear explosives (NE) and high explosives (HE) is approximately equal.[9,10] For shallower depths of burial, NE become increasingly ineffective compared to HE.[11] (C)

Scaling Theory and Analysis

Approach to experimental scaling

(U) 5. Any method of experimental scaling of explosion-produced phenomena depends essentially upon the application of appropriate scaling laws by one of two approaches: (a) by utilizing the same material in the model and the prototype, or (b) by scaling the properties of the prototype material. In most explosion-effects experiments, as a matter of expedience the same materials are used in the model and prototype. If nuclear explosions are to be modeled at small scale, it is necessary to model the prototype material to the degree practicable. The mechanical effects are much the same for HE and NE at confinements exceeding a scaled depth of burial, λ_c , of approximately 0.20 ft/lb$^{1/3}$. For confinements less than this, a calculated equivalence factor relating HE and NE must be employed to relate model HE tests to full-scale nuclear explosions. These "adjusting" calculations do not destroy the accuracy of experimental results; they do, however, affect extrapolation procedures. Depending on the modeling scheme adopted, there are other parameters that may require empirical adjustment. (U)

(U) 6. Generally, the effect of gravity scaling can be ignored because, for the most part, gravity has no direct effect on underground structures except as it produces lithostatic pressures which can be artificially introduced in a model. In a given experiment, a choice must be made

between (a) allowing for gravitation effects and scaling material properties, or (b) ignoring gravity and keeping material properties the same in the model as in the prototype. (U)

Major variables

(U) 7. A list of parameters which might well govern the response of an underground opening or inclusion, along with the scaling relations of these parameters, is provided in table 2. The parameters having the greatest influence on overall response must be selected in accordance with the aims of any given experiment. The paragraphs that follow discuss these parameters and, to a degree, tell how they relate to the scaling of nuclear explosion effects on deep, underground protective structures. (U)

(U) 8. Geometric quantities. The quantities angle, area, volume, and curvature are independent of both the properties of the material and gravity. Thus, if all lengths are properly scaled, geometric scaling is automatic. (U)

(U) 9. Some models need not be geometrically similar to their prototypes, but such similarity is important in the modeling of time-dependent phenomena that are closely related to overall response. In most cases time-dependent phenomena are important parameters of explosion-effects modeling. Also, it is not always practicable to model all features of a prototype in absolute detail, and it is generally accepted that only features that affect the response of a structure to a measurable degree need be modeled. For example, it is not necessary to model every structural detail of an air-vent opening's connection to a deep underground structure in order to determine the collapse pressure of the structures main section. (U)

(U) 10. In modeling a large rock mass, it is necessary for economic reasons to limit the lateral dimensions of the model; whereas a nuclear event of interest may occur at or near the surface of a solid half-space. One primary concern in the design of the model is to make it large enough to record the effects of the incident pulse before the effects of reflected waves are registered (superimposed) upon the incident waves' signature or response. (U)

(U) 11. In homogeneous elastic material, the stress concentration about a circular opening is independent of the opening's size; however, the

ratio of tunnel diameter to the effective length of the strain pulse determines the response mechanism and, very likely, the extent of failure. (U)

(U) 12. Frequency. Frequency has the dimensions of inverse time and should scale as the inverse of scaled time. This means that the rise and decay times will likewise decrease with the model size and will thus have an effect upon the mechanism of failure within closure distances (see section on "Strain and wavelength," paragraphs 31-41). When wavelengths are large compared to the opening dimension, fracture will occur by crushing; when relatively short wavelengths prevail as compared to the dimension of the opening, the response will likely take the form of tensile slabbing. (U)

(U) 13. Velocity. If velocity attenuation due to material properties is ignored, all velocity parameters (shock, sonic, and particle velocity) are the same in the model and prototype when the model and prototype materials are the same. This directly implies that the strain will also be identical, as indicated by the equation

$$v = c\epsilon \tag{1}$$

where v is particle velocity, c is sonic velocity, and ϵ is the strain. (In equation 1, if there is a difference between the velocity of the peak stress or strain rates of propagation and the sonic velocity, velocity of the peak stress should be used for c and not the sonic velocity.) Sonic velocity is given by the equation:

$$c = \left(\frac{\lambda + 2G}{\rho} \right)^{1/2} \tag{2}$$

where c is sonic velocity, λ is Lame's constant, G is the shear modulus of elasticity, and ρ is the mass density. Therefore, equation 1 will hold when material properties are modeled. (U)

(U) 14. Accelerations. If gravitational acceleration is ignored (it should not be when the gravity-induced stresses are a significant part of the medium's strength), the accelerations associated with the stress wave will then scale inversely as the model ratio if inputs are properly scaled, i.e. the smaller the model, the higher the acceleration. Ignoring gravitational acceleration is normally justified because gravity affects only two

parameters related to nuclear attack. The first is the formation of the apparent crater at the surface, which is only indirectly related to the transmitted energy. The second is lithostatic pressure, which is a critical factor in determining the necessary depths for reducing damage to an acceptable level. This may be demonstrated as follows. Utilizing Newmark's equation[12] for stress as related to yield and range,

$$\sigma_r = 25(W)^{5/6}\left(\frac{1000}{R}\right)^{5/2}\left(\frac{c}{1000}\right)^2 \tag{3}$$

where

σ_r = rupture stress, lb/in.^{2}

W = yield of explosive, Mt

R = range, ft

c = sonic velocity, ft/sec

and assuming that the lithostatic pressure is 1 lb/in.^{2} per foot of depth, the combined effects of dynamic and static stress for three yields indicate that for a rock of 25,000 lb/in.^{2} strength there is no depth at which unlined tunnels would survive in a 100-Mt attack (fig. 1). Equation 3 has been modified to fit the results from Project HARDHAT in combination with an analysis of UET data (see "Strain and wavelength," paragraphs 31-41). (U)

(U) 15. Generally, models do not reproduce the scaled effects of lithostatic pressures and are therefore subjected to dynamic stresses only. It is possible, however, to simulate the effects of lithostatic pressures in a model by using a suitable framework and heavy springs for loading to the desired static stress level; or, for a small model, a centrifuge may be used to properly simulate these stresses. (U)

(U) 16. Angular velocity and angular acceleration. These quantities are important parameters only when revolving bodies are being studied; thus, they have no bearing on the problem being considered herein. (U)

(U) 17. Density. When the same materials are utilized in model and prototype, the density ratio is specified, and when one other ratio is fixed, all other model ratios are determined. When different materials are used in model and prototype, a relatively wide choice of density ratios exists. Since compressibility of the materials is often important

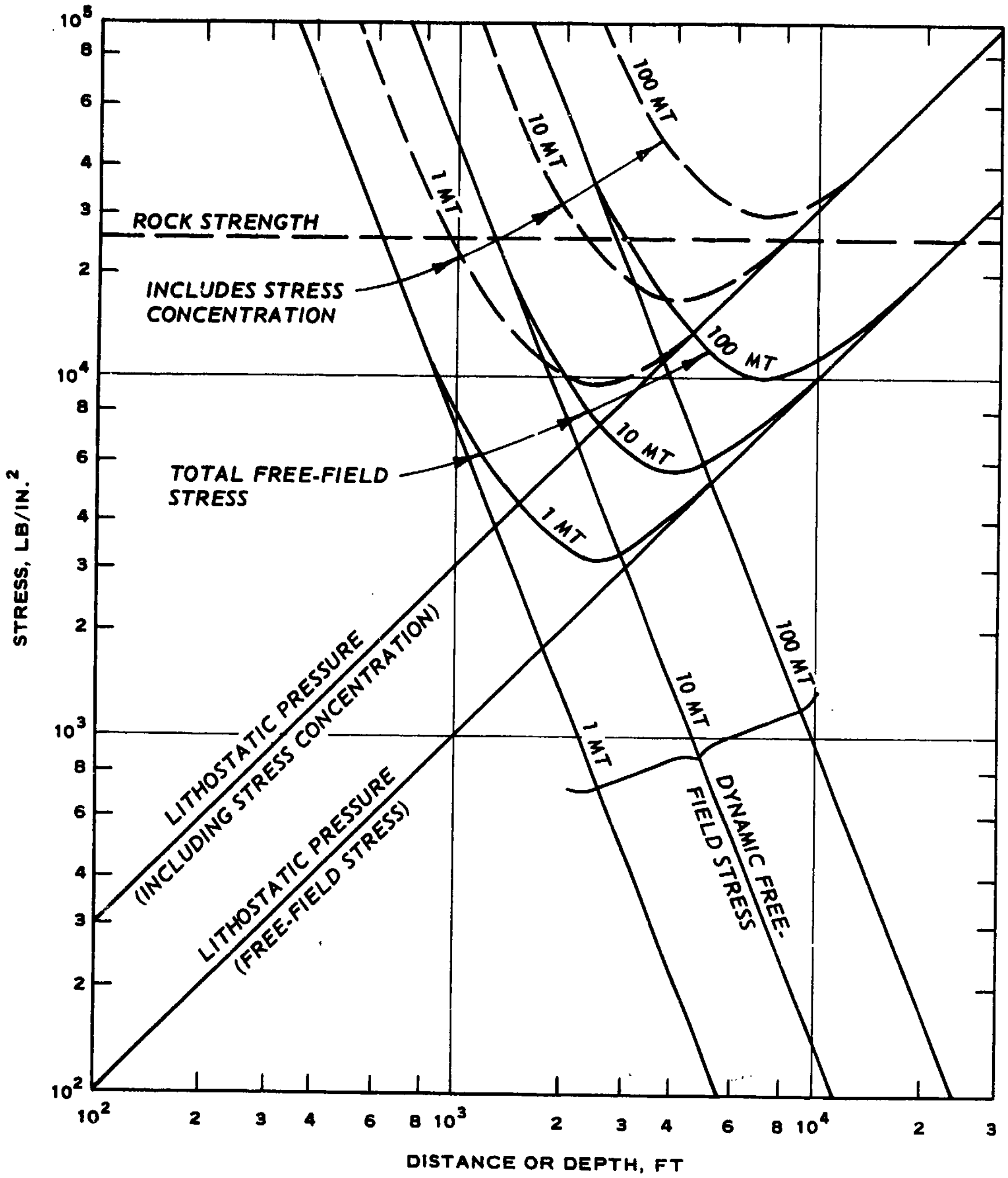

Fig. 1. The effect of superimposing gravity-induced stresses on dynamic free-field stress curves for surface bursts from weapon yields of 1, 10, and 100 Mt

in determining the net response of a system, it is quite unlikely that the density ratio will exceed 5 (prototype density divided by model density). (U)

(U) 18. Momentum, moment of momentum, and angular momentum. Of these three, only the momentum is considered to be significant in the problem under study. An important consideration in evaluating damage and response effects is the conservation of momentum. It is scaled as shown in table 2. (U)

(U) 19. Force. Force scales as the mass or as the model ratio squared, depending on whether or not the materials are scaled. However, stress and pressure are the most significant force parameters of concern in this study. (U)

(U) 20. Total impulse. This parameter varies as shown in table 2. While it has not been demonstrated, there is some indication that the peak stress (or strain) is not the most important factor in producing damage. The duration and magnitude of peak stress (or strain) above a certain critical level, i.e., the equivalent of total impulse above the critical level of stress or strain, appear to be the most important damage parameter. Impulse follows the cube-root law of scaling for similar materials, and may account in part for the fact that closure distances also follow this law (see "Strain and wavelength," paragraphs 31-41). (U)

(U) 21. Torque, power, and action. These quantities scale as shown in table 2, but have no direct application to the general problem being considered in this study.

(C) 22. Work and energy. These quantities vary as the cube of the model ratio for similar materials and, hence, follow the cube-root law. When materials are modeled (gravity and acceleration ratios equal 1), the fourth-root law is applicable. (C)

(U) 23. In the modeling of a large nuclear explosion, two problems arise: (a) determination of the dissipation of energy in the spherically expanding wave, and (b) determination of the equivalence between effective energy yield from NE and HE, particularly for shallow depths of burst. Inasmuch as model studies must employ chemical (HE) explosives, the similarities and differences between the two types of explosives must be evaluated. Early studies of the cratering effects of nuclear explosives led to the erroneous conclusion that chemical explosives are always much more efficient than nuclear explosives. Analysis of more recently acquired cratering data indicates that both types of explosive have approximately the

same crater-producing capability when scaled depths of burial, λ_c , are greater than 0.20 ft/lb$^{1/3}$ (~25 : .t$^{1/3}$). Vaile[11] utilized curves which assumed equal efficiency below a depth closely approximating that given above (λ_c = 0.14 ft/lb$^{1/3}$); and Vortman[9] showed that both are approximately equal in producing craters for conditions of deep burial. Other calculations which resulted in low NE efficiencies[13] appear to be based on the false assumption that there are shock losses in NE but not in HE, and that the efficiency of the latter is dependent only on coupling. The use of 1/3.4 scaling or, in fact, any type of scaling which will normalize crater parameters to a common curve signifies that all charges of that size, whether NE or HE, are of equal efficiency with respect to the phenomena considered and the given parameter. (U)

(C) 24. For reliable model investigations, it is particularly necessary to know the relative efficiencies of shallow HE and NE as compared to completely confined detonations. The methods used by Vaile[11] offer few possibilities because of the uncertainty of choosing a specific and proper scaling law that is applicable to shallow explosions. (C)

(C) 25. If it is assumed that for scaled depths (cube-root scaling) of burial less than λ_c = 1.0 ft/lb$^{1/3}$ the apparent (or true) crater volume, radius, or depth is a measure of the shock energy input into the earth below the crater, then approximate relative efficiencies can be determined. The energy directed downward into the earth approaches a maximum at a burial depth of λ_c = 3.0 ft/lb$^{1/3}$, and cratering parameters approach a maximum at 1.0 ft/lb$^{1/3}$ depending upon charge size. That is, when cube-root scaling is used, the maximum values of the scaled radius, volume, and depth tend to decrease with increase in yield. (C)

:) 26. Apparent crater radii in desert alluvium, which approximate the ue crater radii in this medium, vary with yield and scaled depth as shown in fig. 2. The curves, based upon cube-root scaling, are shown as two straight-line segments. These curves were derived from the data given in table 3 and are for radii at equal scaled depths of burial over the HE ranges from 256 to 40,000 lb, and for NE yields up to 100 kt. The position of the λ_c = 0 (NE) line was determined largely on the basis of the JANGLE S and JOHNIE BOY events. The relative radius-producing efficiency, easily determined for any two events at a scaled depth of

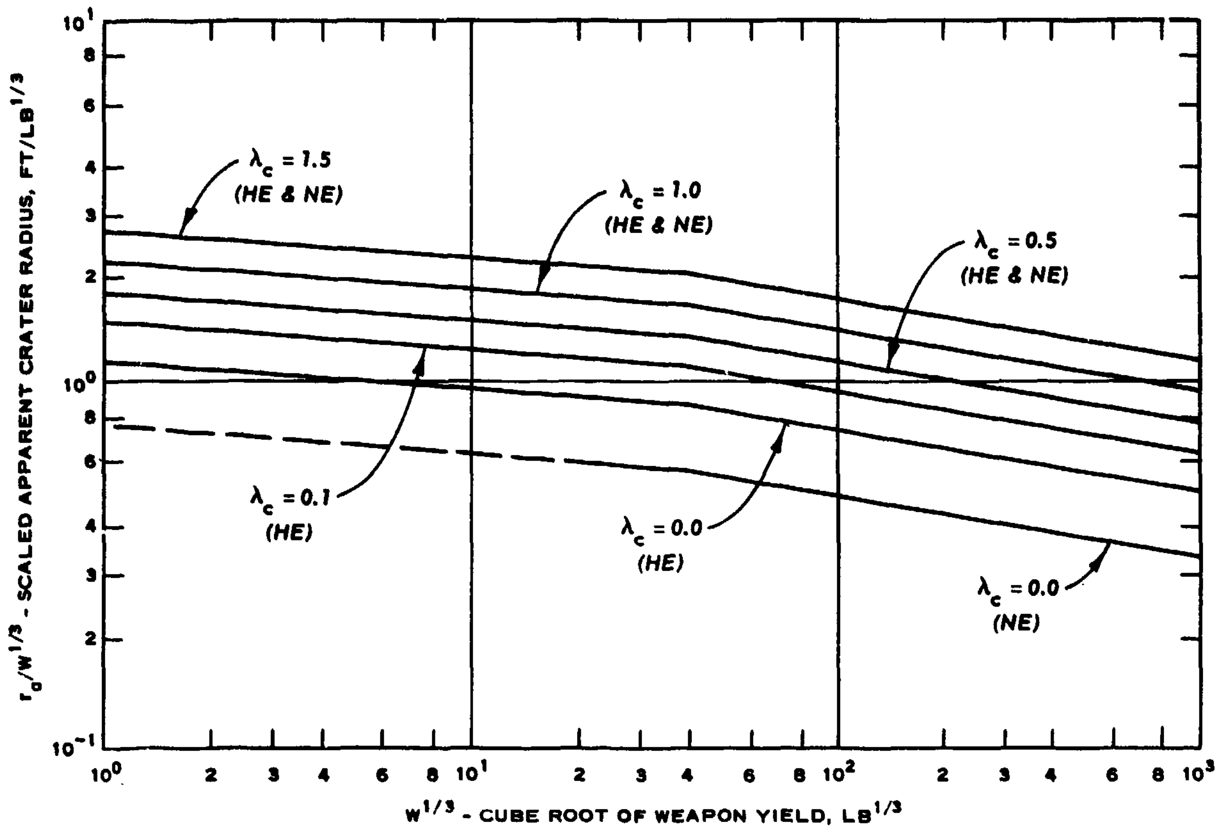

Fig. 2. Variation of scaled apparent crater radius with cube root of weapon yield

1.0 $ft/lb^{1/3}$, can also be considered a measure of the relative strain-producing efficiency. These values for various scaled depths of burst were utilized in connection with the strain-producing efficiency for HE in granite[14] as a basis for predicting the effects of very large HE or NE charges (fig. 3). (C)

(C) 27. The data in table 4 (all from events having yields of from 0.5 to 1.2 kt except SEDAN which had a yield of 100 kt) show that radii efficiencies are not a good measure of relative efficiencies for above-surface shots (JANGLE S), but are appropriate for depths of burial as deep as $\lambda_c = 1$. The plot of scaled crater radius versus yield (fig. 2) indicates that the crater radius-producing ability of NE decreases with increasing weapon yield approximately as that of HE except at shallow burials, where the specific crater radius is smaller for NE. This percentage of energy efficiency is somewhat larger than that suggested by Newmark.[12] The crater radius-producing efficiency of HE is much higher than that of NE for detonations both immediately above and below the surface. (C)

(C) 28. For burial depths greater than $\lambda_c = 0.20\ ft/lb^{1/3}$, the efficiency of NE rapidly approaches that of HE. This is supported by the following conclusions from references 9 and 10:

- a. The apparent crater parameters for both NE and HE detonations are approximately the same when the scaled depths of burial are equal (fig. 2).[9]
- b. Peak strains from completely confined NE and HE explosions of equal yield follow approximately the same law at equal scaled distances.
- c. An analysis of the gross thermodynamic processes taking place within the final cavity limits produced by both types of explosive indicates that the heat losses in NE processes may be less than 10 percent greater than those in HE, the former being due to the heats of fusion and vaporization of rock etc., which represent relatively small irrecoverable energy losses.[10]
- d. Shock losses associated with HE and NE should be approximately equal.
- e. The cube root-scaled closure distance for HARDHAT (an NE

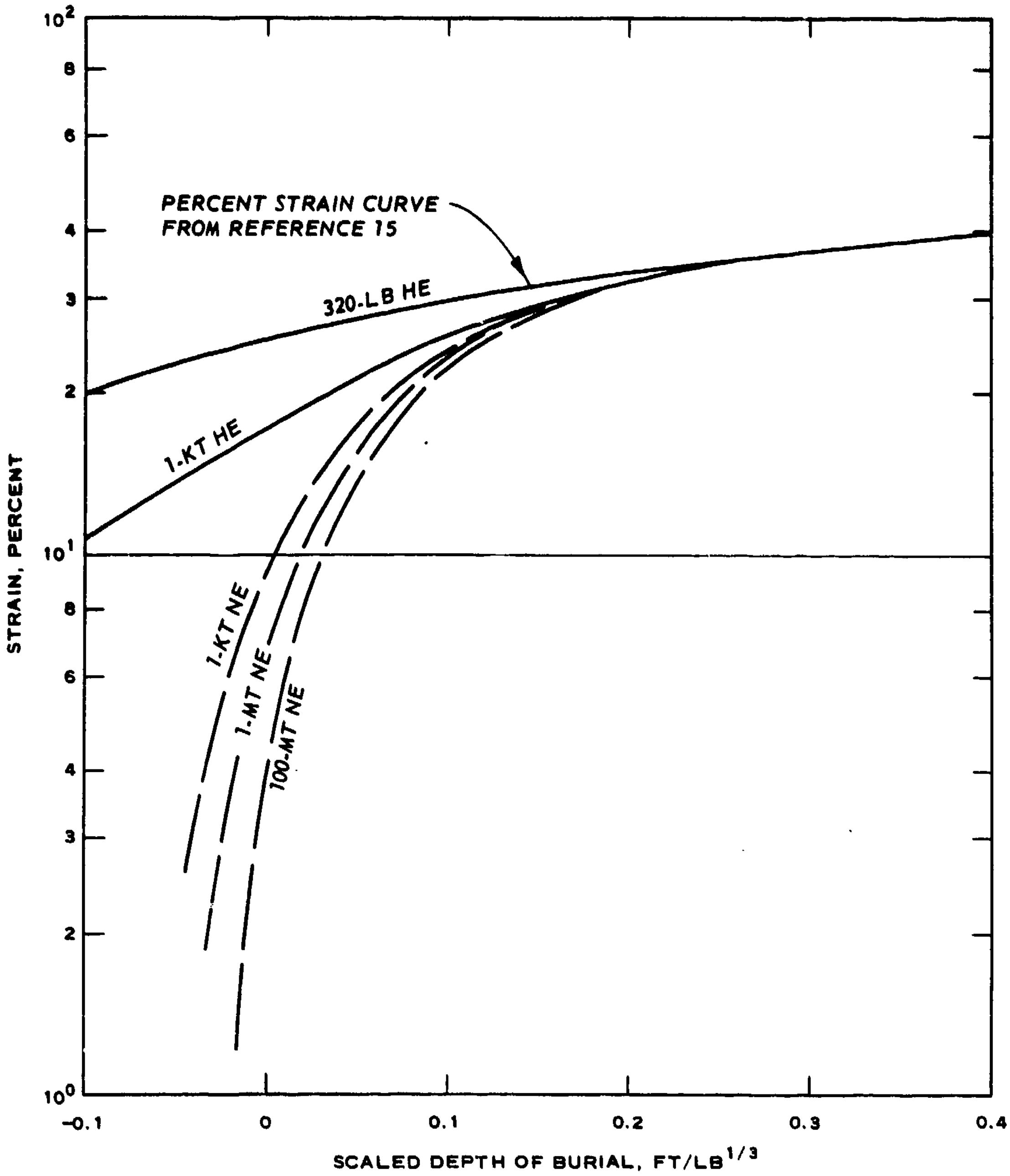

Fig. 3. Percent strain produced relative to completely contained charges, based on extrapolation of curve from reference 15 together with crater radius curves versus yield for desert alluvium

experiment) was greater than for UET HE experiments even allowing for the relatively shallow burial ($\lambda_c = 0.36$ lb/ft$^{1/3}$) of the UET detonations.

f. With the exception of the strain and velocity pulse lengths from SHOAL, the NE and HE values obey a common scaling law for UET and HARDHAT when adjustments are made for the charge size.

g. Subsidence craters created by completely confined NE and HE obey a common cube-root law.[9] (C)

(C) 29. Thus, for experimentation with models, chemical explosives may be used to simulate nuclear explosives on a 1:1 basis for confinements varying from complete to scaled depths of burst approaching a minimum value of $\lambda_c = 0.20$ ft/lb$^{1/3}$. For shallower depths an equivalence factor must be used. (C)

(C) 30. Stress, pressure, and strength. Theoretically, these quantities all have 1:1 values at the same scaled range in a model composed of the same material as the prototype. However, if the prototype is scaled to the megaton range, the stress at given scaled ranges from the explosive will be decreased by attenuation factors not otherwise accounted for by similitude. Thus, model results should give higher values for dynamic stress than the prototype; however, this may be more than compensated for by the stress due to lithostatic or tectonic pressure (see figs. 4 and 5). The attenuation can be accounted for by utilizing an expression which includes attenuation (see "Strain and wavelength" below). When properties of materials are modeled but with density ratio equal to 1, then the stresses and strengths vary as the first power of the model ratio. (C)

(C) 31. Strain and wavelength. The peak strain has been justifiably regarded by Newmark[16] as one of the more important design parameters for tunnel linings and packing behind the liners. The crushing of rock around a tunnel liner is assumed to be accompanied by bulking, and the range, R_{cd} , at which crushing in granite will cease is given for a contained burst by the equation

$$\frac{\epsilon_u}{3} = 0.0033 = 0.01 \text{ in./in.} \left(\frac{W}{1 \text{ Mt}} \right)^{5/6} \left(\frac{1000}{R_{cd}} \right)^{5/2} \qquad (4)$$

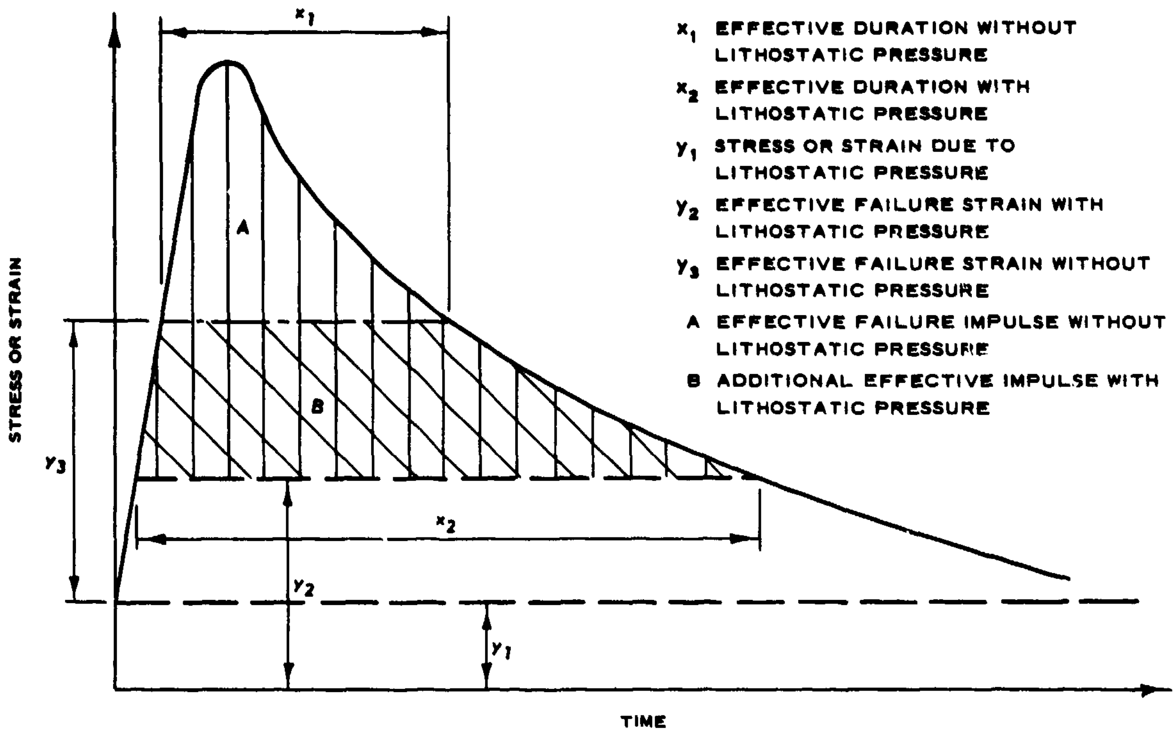

Fig. 4. Schematic of stress or strain versus time illustrating the effects of lithostatic pressure

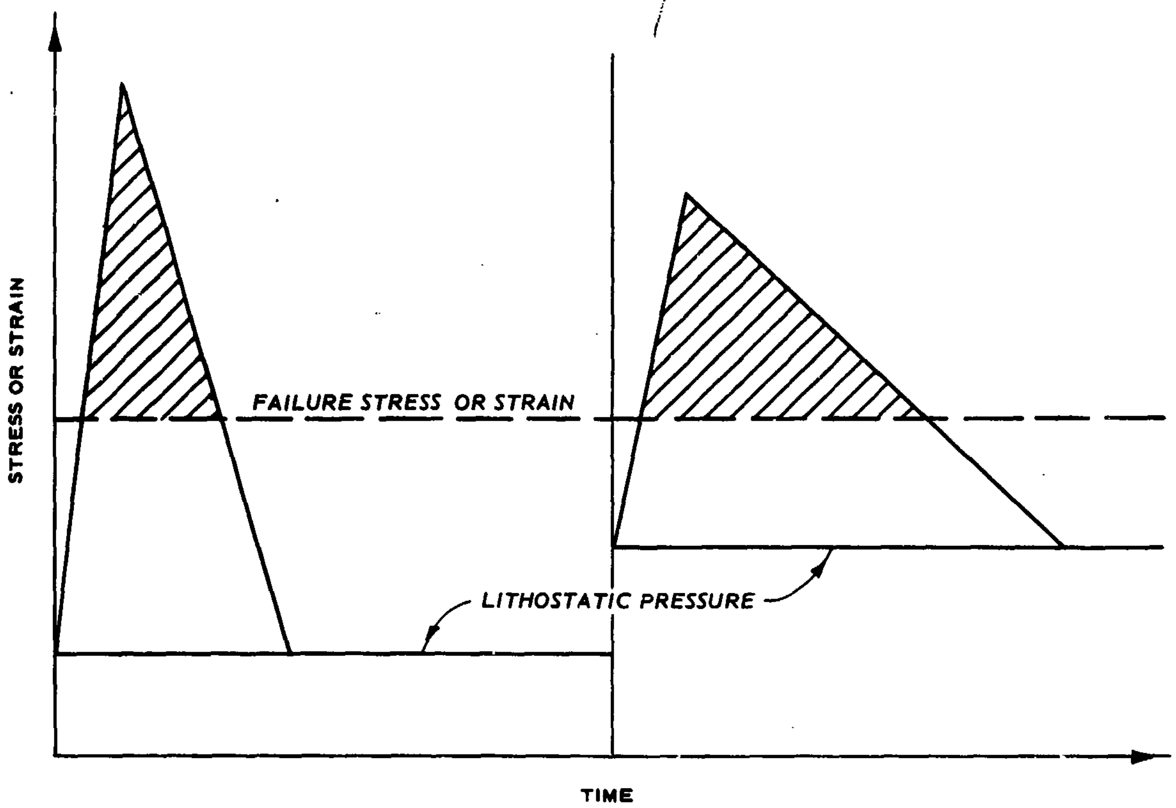

Fig. 5. Schematic showing how total impulse is maintained with increase in pulse length and decrease in peak dynamic strain, the latter being increased by the lithostatic pressure with increased weapon yield and depth of underground structure

where ϵ_u is ultimate strain,[11] W is the explosion yield in Mt, and R_{cd} is the critical range at which crushing ceases. Beyond the distance R_{cd}, there will be some crushing and failure of zone 2 severity (continuous spalling but with decreasing thickness). (C)

(C) 32. The net response is thus related to the length of the strain pulse, which has been shown to increase approximately as the first power of travel distance. Also, the pulse duration is a function of yield and is given by the following empirical equation which was derived from fig. 6.

$$t = 0.038\, W^{0.4} \left(\frac{R}{W^{1/3}} \right) \tag{5}$$

where t is pulse duration, R is range, and W is the explosion yield in pounds. (C)

(C) 33. The only available strain data for very small charges are for Kanawa sandstone and Lithonia granite[17] which have properties similar to Navajo sandstone and HARDHAT granite. However, charges were fired at various scaled depths, and hence the curve for small charges is included for reference only. (C)

(C) 34. Another condition which increases the effective strain is the lithostatic pressure, i.e., the rock is already under vertical compressive strain due to the weight of the overlying rock. This is illustrated in figs. 1, 4, and 5 which indicate that the lithostatic pressure not only increases the magnitude, but also the duration of the effective strain. (C)

(C) 35. Thus, the values of strain and pulse duration should be increased by a factor which is a linear function of depth , d :

$$\epsilon = k \left(\frac{W}{1\ \mathrm{Mt}} \right)^{5/6} \left(\frac{1000}{R} \right)^{5/2} \cdot d \tag{6}$$

$$t = k\, W^{0.4} \left(\frac{R}{W^{1/3}} \right) \cdot d \tag{7}$$

In equation 6, ϵ is the strain (dimensionless), k is a constant, W is the explosion yield in Mt, R is the range in feet, and d is the depth for a given observation in feet. In equation 7, t is the shock duration in msec, k is a constant, W is the weight of charge in pounds, and R is the range in feet. These depth factors may be at least partially responsible

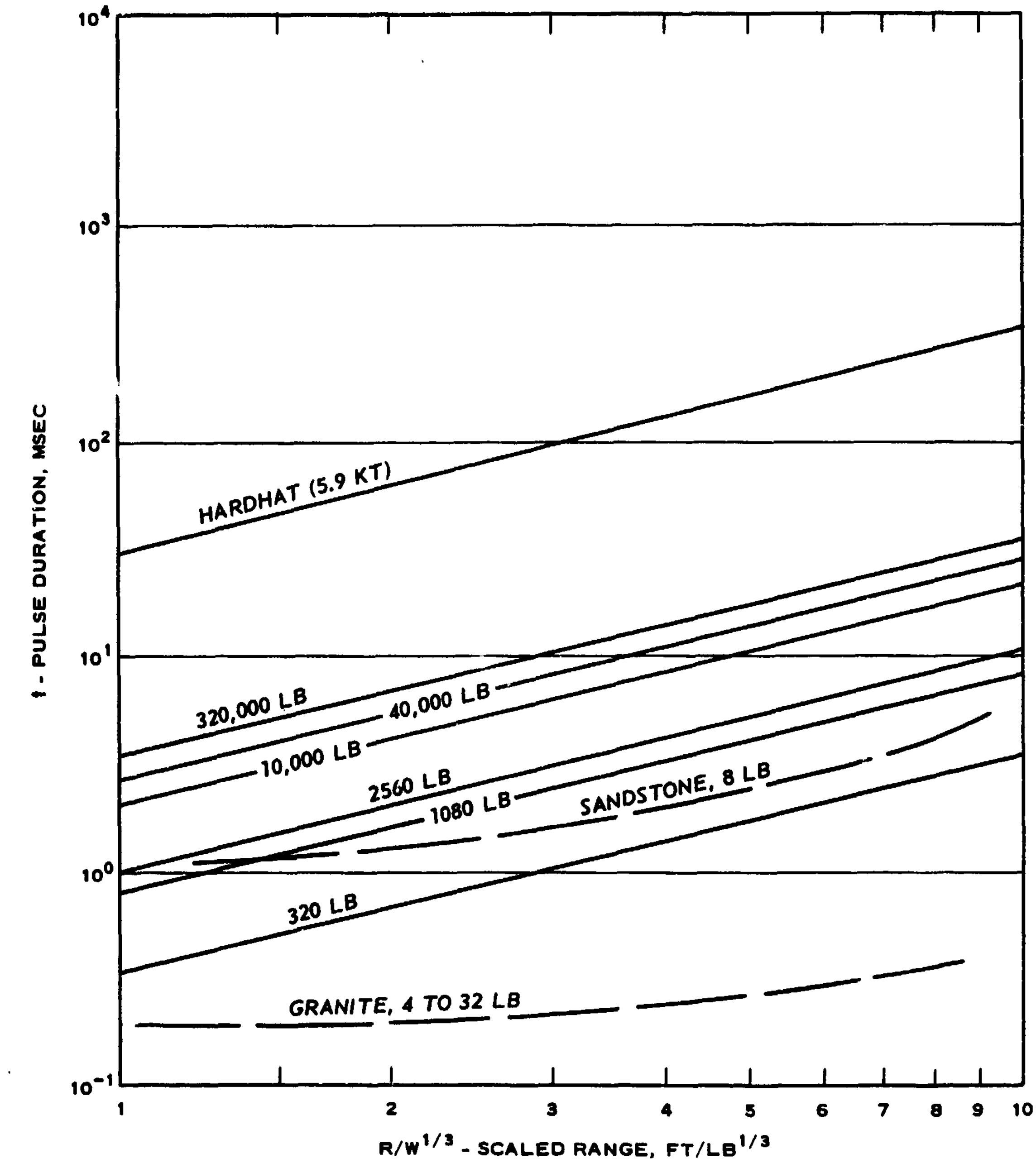

Fig. 6. Variation of pulse duration with weapon yield and scaled range. HARDHAT in granite; HE in sandstone and granite

for the fact that the HARDHAT closure distance was larger than predicted. A further modification of the above strain equation is developed in paragraph 37. (C)

(C) 36. The maximum strain that the rock medium will sustain without failure and thus transmit to the rock located in the direction of propagation is determined by the breaking strain of the rock under the particular conditions of confinement at the time it is traversed by the pressure wave. This strength, in turn, also defines the limit of the fracture zone. The properties of rock in the UET and HARDHAT programs are listed in table 5. (C)

(C) 37. Still other factors which may partially account for the greater scaled closure distance for HARDHAT are the lower strain at rupture, and the fact that there is less than half the energy under the stress-strain curve at failure for HARDHAT granite as for UET (Unaweep) granite. If the rock is elastic, the higher Young's modulus for HARDHAT granite would have the effect of increasing the seismic velocity, thus decreasing the length of the pulse. Generally, the slope of the peak strain versus scaled range curve for granite is taken to be -2.5. The plot of points for 320-lb shots at $\lambda_c = 3.64 \text{ ft/lb}^{1/3}$, which is assumed to approach complete confinement, and the peak strains for HARDHAT and SHOAL granite with RANIER tuff data added for comparison (fig. 7), and similar curves for sandstone (fig. 8), give the following peak strain equation:

$$\epsilon = 0.08\, W^{-1/9} \left(\frac{R}{W^{1/3}} \right)^{-5/2} \tag{8}$$

where the constant 0.08 has dimensions of $W^{1/9}$, W is in pounds, and R is in feet. That is, the peak strain is a function of charge size as well as scaled range. The data from SHOAL were not employed to obtain the multiplier for the $R/W^{1/3}$ term, and the exponent of W would be a little smaller than 1/9 if these were included. The strain equation thus becomes an expression for a family of curves, and this fact should be kept in mind when the equation is employed for prediction purposes. Equation 8 for confined explosions may be converted to the form used by Newmark for range in thousands of feet and yield in megatons:

$$\epsilon = 0.004 \left(\frac{W}{1\ \text{Mt}} \right)^{2/3} \left(\frac{1000}{R} \right)^{5/2} \tag{9}$$

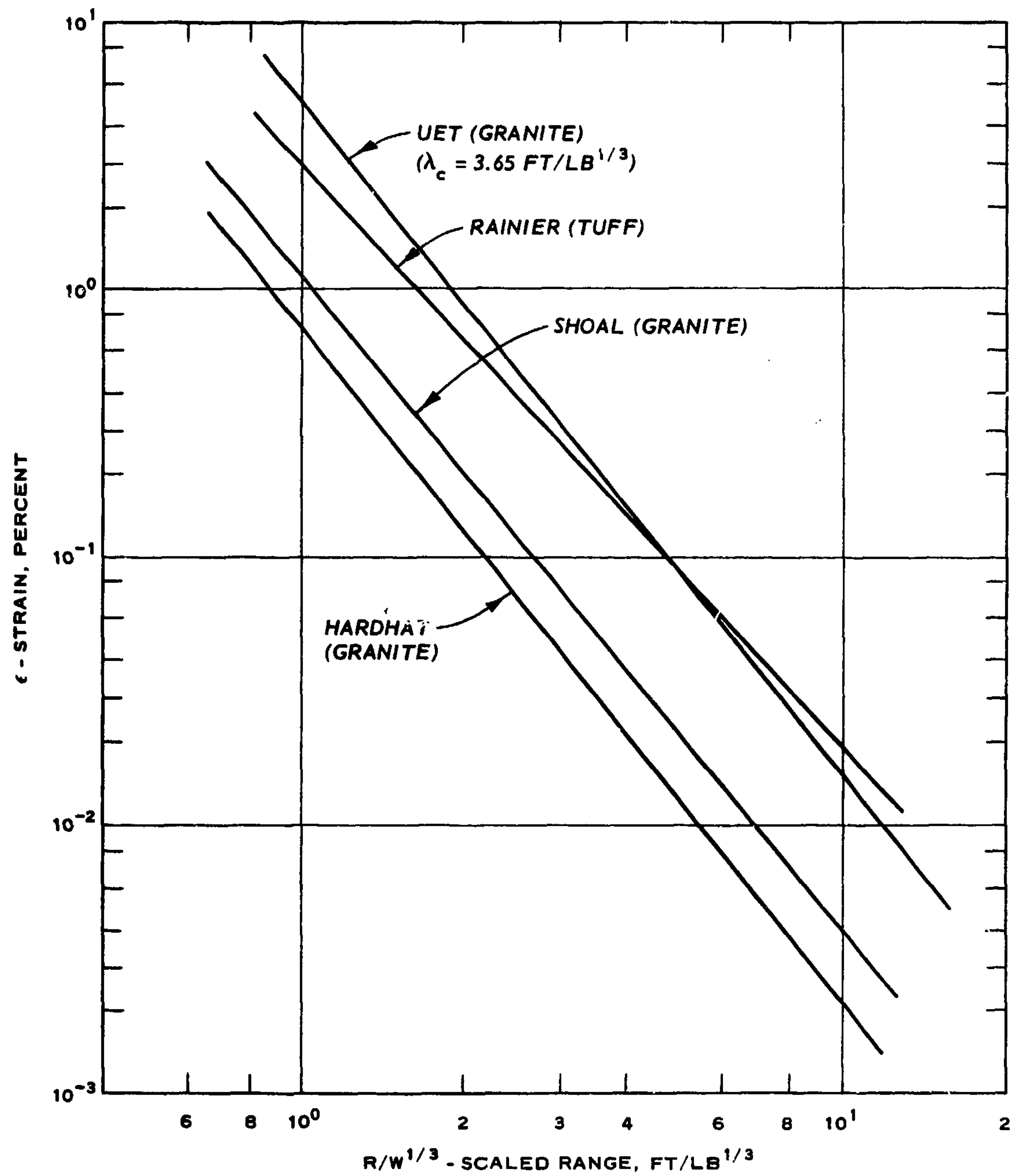

Fig. 7. Strain versus scaled range for UET (320 lb), HARDHAT (5.9 kt), RAINIER (1.7 kt), and SHOAL (10 kt)

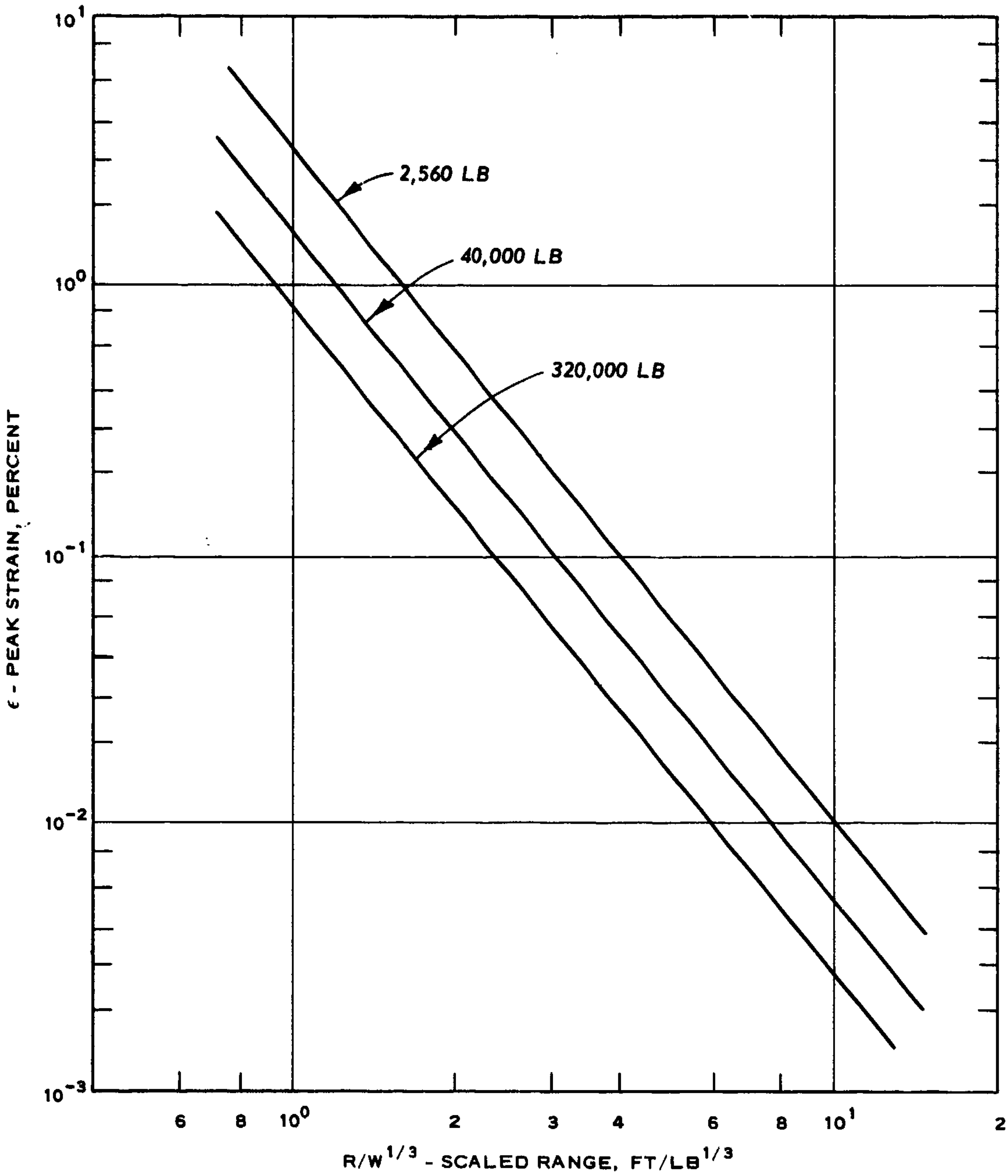

Fig. 8. Variation of peak strain in Navajo sandstone with scaled range for specific charge weights ($\lambda_c = 0.36$)

(C) 38. It is also assumed that the energy effects of NE and HE are equal for confined detonations and for buried detonations below a scaled depth of $\lambda_c = 0.20$ ft/lb$^{1/3}$. For near-surface events, the equivalence can be closely approximated as follows: The crater radius appears to be a fair measure of the relative amount of energy transmitted to the earth. The plot of radii for significant HE and NE events (fig. 2) also indicates that for contact bursts, NE is approximately 60 percent as effective as HE. Utilizing also the effect of depth as measured from the UET 320-lb shots, the strain energy from near-surface NE explosions can be approximated (fig. 3). It is found that the equivalence for 1 kt at the surface is about 9.5 percent, and that for 1 Mt about 6 percent, the percentage decreasing by about 1 percent for each order of magnitude increase in yield. Thus for the 1-Mt range, the strain equation for a surface burst becomes

$$\epsilon = 0.004(0.06\ W)^{2/3} \left(\frac{1000}{R} \right)^{5/2} \tag{10}$$

or

$$\epsilon = 0.0006(W)^{2/3} \left(\frac{1000}{R} \right)^{5/2} \tag{11}$$

This compares favorably with the equation recommended by Newmark[12] with the exception of the exponent of the yield which is 2/3 instead of 5/6 (fig. 9). (C)

(C) 39. Young's modulus (E) for HARDHAT granite is 11.8×10^6 lb/in.^{2} and the seismic velocity equals 18,000 ft/sec. The stress equation thus becomes

$$\begin{aligned} \sigma_r &= \epsilon_r E = 36{,}400 \times 0.0006\ W^{2/3} \left(\frac{1000}{R} \right)^{5/2} \left(\frac{c}{1000} \right)^2 \\ \sigma_r &= 22\ W^{2/3} \left(\frac{1000}{R} \right)^{5/2} \left(\frac{c}{1000} \right)^2 \end{aligned} \tag{12}$$

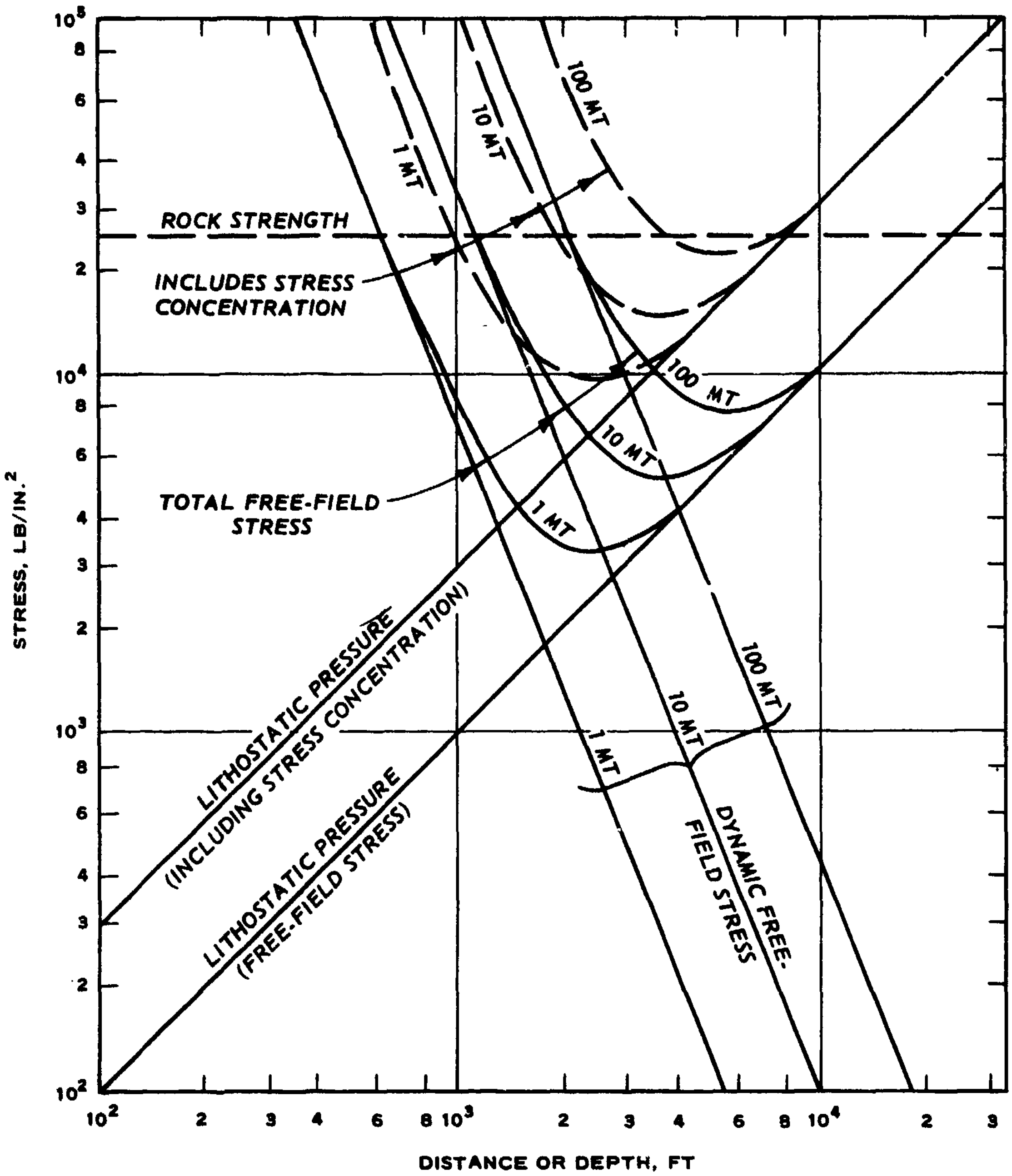

Fig. 9. Effect of superimposing gravity-induced stresses on dynamic free-field stress curves for weapon yields of 1, 10, and 100 Mt (surface bursts). Differs from fig. 1 because of the use of the modified stress equation 12

Again, W is in Mt, R is in feet, and c is in ft/sec; ϵ_r is radial strain. The stress equation is also logically in close agreement with Newmark with the exception of the yield exponent. (C)

(C) 40. The reduction of the yield exponent from 5/6 to 2/3 reduces predicted peak stress for multimegaton bursts. Newmark[16] maintained that the peak strain is the most reliable criterion for design purposes. Clark[18] proposed that both the magnitude and the duration of the pulse above a critical level are important along with the related energy density. A plot of all available data for closure distances versus yield shows that values all fall within a scaled range of 1.29 to 2.00 (fig. 10). Excluding tuff, the range is 1.65 to 2.00. If UET results are adjusted to account for the fact that burial depths were only 0.36 ft/lb$^{1/3}$, and ERDL results in basalt are adjusted to account for the low loading density, then all closure distances (except in tuff) for large yields (>750 lb) fall very close to 2.00 ft/lb$^{1/3}$. Thus, the scaled closure distance, d_c, in feet (fig. 10) can be expressed mathematically as

$$d_c = k\, W^{1/3} \tag{13}$$

If the peak strain is multiplied by the strain period the following results:

$$\begin{aligned} \epsilon \times t &= k_o\, W^{1/3} \left(\frac{R}{W^{1/3}} \right)^{-1.5} \\ \epsilon \times t &= k_o\, W^{1/3}\, (\lambda_r)^{-1.5} \end{aligned} \tag{14}$$

That is, at a given scaled range, λ_r, the product of the peak strain and pulse duration varies approximately as the cube root of the yield. This is analogous in form with the closure equation (equation 13), which indicates that a more basically correct design criterion is the product of the strain and its duration. The later is assumed to be proportional to the area under the strain-time curve. (C)

(C) 41. There is no immediately obvious explanation for the smaller closure distances occurring in tuff. The lithostatic pressure would be almost comparable to that of HARDHAT. Hence, the greater resistance of tuff to closure must be attributed to its physical properties. Two

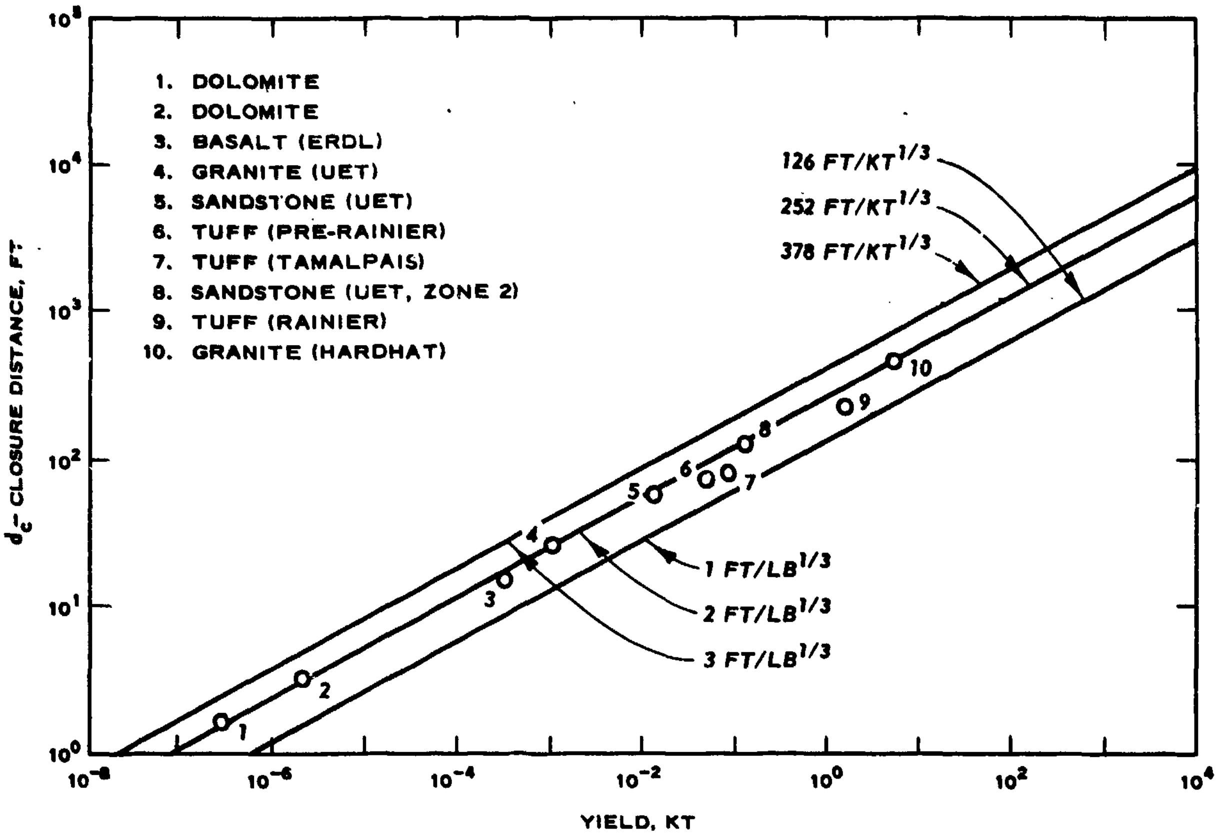

Fig. 10. Tunnel closure distance versus yield for contained explosions

properties that are radically different from those of the other rocks studied are the compressive strength and Young's modulus. Thus, while the magnitude of strain in the RAINIER wave was larger than that of HARDHAT, the relative "elastic" energy would have been $1/2 \times 1500 \times 0.007 = 0.525$ for tuff compared to $1/2 \times 1500 \times 0.002 = 12.5$ for HARDHAT granite, or approximately 25 times as great for the latter. While these figures are for unconfined rock, they are strongly indicative of the reason for the resistance of tuff, or conversely, its inability to sustain waves at high energy and strain levels. (C)

(U) 42. In a model wherein the properties of the material are scaled, the impedance varies as $\rho\lambda^{1/2}$ where λ is the ratio between prototype and model length; and if the densities are the same, the impedance will vary as $\lambda^{1/2}$ or as the velocity ratio. In a model which has the same properties as the prototype, the impedances of the two are identical. In either case, impedance matching requires that ρc of both model and prototype explosions and materials should be scaled according to the selected model criteria. (U)

(C) 43. In the calculation of impedance matching of explosives to rock, the Bureau of Mines[15,19-22] uses detonation velocity as the impedance velocity parameter. Inasmuch as the detonation state exists only for a very small period of time relative to the effective pressure pulse of a confined explosive, it would appear more logical to employ the density and sonic velocity of the explosion state. A comparable parameter for nuclear explosives is not so evident. (C)

Conclusion

(C) 44. Analysis of data from small- and large-yield explosion experiments indicates that:

a. For depths of burial greater than 0.20 $ft/lb^{1/3}$ ($\sim$25 $ft/kt^{1/3}$) HE and NE are approximately of equal effectiveness; for shallower burial, an equivalence factor must be used.

b. Large-scale surface explosions can be modeled using confined charges and an equivalence factor.

c. Model experiments can be conducted by either scaling material properties or using the same material in the model as exists in the prototype.

d. Lithostatic pressure, which can be modeled artificially, produces significant stress for depths greater than 3000 ft; therefore, the lithostatic stresses should not be neglected when attempting to model explosion effects on structural inclusions that are deeper than 3000 ft in the prototype.

e. Scaled closure distances agree closely with the cube-root law with some allowance made for variation in material properties.

f. Peak strain multiplied by pulse duration scales as the cube root of yield for given scaled ranges. This parameter plus energy density are believed to be the important ones for design purposes. (C)

(C) 45. The foregoing analysis indicates that model scaling can be used to advantage to investigate a number of the factors which are important in the response of deep underground structures to explosive attack. (C)

Recommendations

(C) 46. It is recommended that:

a. The present investigation be pursued by experimentation both with models which scale the properties of the material and those which utilize material in the model which has the same properties as the prototype.

b. Model studies of the effect of geologic structures be investigated.

c. Attempts be made to model lined tunnels with the linings backed by various packings, as well as to use models to study vibration effects on spring-mounted structures.

d. Factors related to modeling, such as NE-HE equivalence, effects of shallow burial, and coupling, be investigated to permit more extensive extrapolation of model results. (C)

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Table 1

Scaled Closure Distances for Contained HE and Nuclear Detonations*

Event	Tunnel Material	Tunnel Configuration	Distance Zero Point to Closure ft	Angle of Incidence Zero Point to Closure deg	Yield	Distance to Point of Closure: Scaled to 1 kt, ft	Distance to Point of Closure: Scaled to 1 lb, ft/lb$^{1/3}$	Outer Limit Zone 4 Scaled to 1 kt, ft
HARDHAT	Granite	Confined	360	90	5.9 kt	260	2.00	702
RANIER, U-12b	Tuff	Hooked**	200	14	1.7 kt	168	1.29	420
TAMALPAIS, U-12b.02	Tuff	Hooked	80	28	0.09 kt	179	1.37	420
LOGAN, U-12e.02	Tuff	Straight	820	35	4.5 kt	496	3.82	1190
EVANS, U-12b.04	Tuff	Hooked	Unknown	--	0.045 kt	Unknown	--	Unknown
BLANCA, U-12e.05	Tuff	Straight**	870	16	23 kt	306	2.36	690
UET	L sandstone	Confined	120 (zone 2)	90	0.16 kt (HE)	220	1.69	--
UET	Granite	Confined	19	90	2560 lb	181	1.39	--
ERDL	Basalt	Confined	15	90	750 lb	175	1.35	--
PRE-RANIER	Tuff	Confined	76	40	50 ton	213	1.64	--
DOLOMITE	--	Confined	1.5	90	0.8 kt	215	1.65	--
DOLOMITE	--	Confined	3.0	90	1.6 kt	215	1.65	--

* Adapted from reference 8 of Selected Bibliography.
** With venting to the unusable portion of the drift beyond the zero point.

Table 2

Model Ratios of Mechanical Quantities*

Scaling Parameters	(1) Dimensional Formula	(2) Model Ratio	(3)** $a_p = a_m$	(4)** $\rho_p = \rho_{2m}$ $V_p = V_{2m}$
Acceleration	LT^{-2}	$\lambda\tau^{-2}$	1	λ^{-1}
Action	ML^2T^{-1}	$\mu\lambda^2\tau^{-1}$	$\mu\lambda^{3/2}$	λ^4
Angle	L^0	1	1	1
Angular acceleration	T^{-2}	τ^{-2}	λ^{-1}	λ^{-2}
Angular momentum	ML^2T^{-1}	$\mu\lambda^2\tau^{-1}$	$\mu\lambda^{3/2}$	λ^4
Angular velocity	T^{-1}	τ^{-1}	$\lambda^{-1/2}$	λ^{-1}
Area	L^2	λ^2	λ^2	λ^2
Curvature	L^{-1}	λ^{-1}	λ^{-1}	λ^{-1}
Density	ML^{-3}	$\mu\lambda^{-3}$	$\mu\lambda^{-3}$	1
Elastic modulus	$ML^{-1}T^{-2}$	$\mu\lambda^{-1}\tau^{-2}$	$\mu\lambda^{-2}$	1
Force	MLT^{-2}	$\mu\lambda\tau^{-2}$	μ	λ^2
Frequency	T^{-1}	τ^{-1}	$\lambda^{-1/2}$	λ^{-1}
Gravitational constant	$M^{-1}L^3T^{-2}$	$\mu^{-1}\lambda^3\tau^{-2}$	$\mu^{-1}\lambda^2$	λ^{-2}
Impedance (ρc)	$ML^{-2}T^{-1}$	$\mu\lambda^{-2}\tau^{-1}$	$\mu\lambda^{-5/2}$	1
Kinematic viscosity	L^2T^{-1}	$\lambda^2\tau^{-1}$	$\lambda^{3/2}$	λ
Length	L	λ	λ	λ
Moment of momentum	ML^2T^{-1}	$\mu\lambda^2\tau^{-1}$	$\mu\lambda^{3/2}$	λ^4
Momentum	MLT^{-1}	$\mu\lambda\tau^{-1}$	$\mu\lambda^{1/2}$	λ^3
Power	ML^2T^{-3}	$\mu\lambda^2\tau^{-3}$	$\mu\lambda^{1/2}$	λ^2
Strain	L^0	1	1	1
Stress, pressure, and strength	$ML^{-1}T^{-2}$	$\mu\lambda^{-1}\tau^{-2}$	$\mu\lambda^{-2}$	1
Time	T	τ	$\lambda^{1/2}$	λ
Torque	ML^2T^{-2}	$\mu\lambda^2\tau^{-2}$	$\mu\lambda$	λ^3
Total impulse	MLT^{-1}	$\mu\lambda\tau^{-1}$	$\mu\lambda^{1/2}$	$\lambda^{3/2}$
Total impulse area	$ML^{-1}T^{-1}$	$\mu\lambda^{-1}\tau^{-1}$	$\mu\lambda^{-3/2}$	λ
Velocity	LT^{-1}	$\lambda\tau^{-1}$	$\lambda^{1/2}$	1
Viscosity	$ML^{-1}T^{-1}$	$\mu\lambda^{-1}\tau^{-1}$	$\mu\lambda^{-3/2}$	λ
Volume	L^3	λ^3	λ^3	λ^3
Wavelength	L	λ	λ	λ
Work and energy	ML^2T^{-2}	$\mu\lambda^2\tau^{-2}$	$\mu\lambda$	λ^3

* See glossary for definition of symbols.

** a, ρ, and V stand for acceleration, density, and velocity, respectively. The subscripts p and m stand for prototype and model, respectively.

Table 3

Crater Radius Data From Full-Scale HE and NE Shots

Project	Shot Designation	Charge Weight, W lb	$W^{1/3}$ $lb^{1/3}$	Apparent Crater Radius r_r, ft	Depth of Burst Z, ft	Scaled Apparent Crater Radius $\left(r_a/W^{1/3}\right)$ $ft/lb^{1/3}$	Scaled Depth of Burst $\left(\frac{Z}{W^{1/3}}\right)$ $ft/lb^{1/3}$
			HE				
JANGLE HE	HE-1	2,560	13.7	18.50	1.35	1.35	0.10
	HE-7	2,560	13.7	19.00	2.60	1.39	0.19
	HE-6	2,560	13.7	19.80	3.01	1.45	0.22
	HE-5	2,560	13.7	19.40	4.10	1.42	0.30
	HE-3	2,560	13.7	20.27	6.84	1.48	0.50
	HE-2	40,000	34.2	39.00	5.13	1.14	0.15
MOLE	206	256	6.35	6.35	0.00	1.00	0.00
	205	256	6.35	8.90	0.83	1.40	0.13
	204	256	6.35	9.45	1.65	1.49	0.26
	203	256	6.35	8.35	3.17	1.31	0.50
	202	256	6.35	11.40	6.35	1.80	1.00
	212	256	6.35	11.20	6.35	1.76	1.00
SANDIA SERIES I	8	256	6.35	13.13	6.35	2.07	1.00
	2	256	6.35	15.12	9.53	2.38	1.50
	9	256	6.35	14.14	9.53	2.23	1.50
SANDIA SERIES II	S-12	256	6.35	8.57	0.00	1.35	0.00
	S-13	256	6.35	8.34	0.00	1.31	0.00
SCOOTER		1×10^6	100	154	125	1.54	1.25
STAGECOACH	2	40,000	34.2	50.5	17.1	1.48	0.50
	3	40,000	34.2	58.6	34.2	1.71	1.00
			NE				
SEDAN		2×10^8	585	640	633	1.09	1.08
TEAPOT ESS		2.4×10^6	134	146	67	1.09	0.50
JANGLE S		2.4×10^6	134	45	-3.5	0.34	-0.026
JANGLE U		2.4×10^6	134	129	17.0	0.96	0.127
JOHNIE BOY		1.0×10^6	100	61	2.7±	0.61	0.03

Table 4

Apparent Volume and Radius Efficiencies of Full-Scale HE and NE Shots

Project	Charge Weight lb	λ_c ft/lb$^{1/3}$	$r_a/W^{1/3}$ ft/lb$^{1/3}$	%	$V/W^{1/3}$ ft^3/lb$^{1/3}$	%
SCOOTER (HE)	1×10^6	1.25	1.54	100	2.64	100
SEDAN	2×10^8	1.08	1.11	72	0.90	34
TEAPOT ESS	2.4×10^6	0.50	1.09	71	1.08	40.8
JANGLE S	2.4×10^6	-0.026	0.34	22	1.85×10^{-3}	0.07
JANGLE U	2.4×10^6	0.0127	0.96	62	0.42	16
JOHNIE BOY	$1 \times 10^6 \pm$	0.03±	0.61	40	0.15	6

Table 5

Properties of UET and HARDHAT Rocks

Property	Unaweep Granite	Navajo Sandstone	HARDHAT Granite
Tensile strength, psi	500	100	10,000
Compressive strength, psi	25,000	4800-8600	25,000
Young's modulus of elasticity, psi	$3.4\text{-}5.4 \times 10^6$	$1.5\text{-}2.5 \times 10^6$	11.3×10^6
Modulus of rupture, psi	2,300	600	1,900*
Strain at compressive failure, psi	0.004-0.007	0.003-0.006	0.002

* Splitting strength.

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13. ABSTRACT (U) An analysis is presented of the scaling parameters which are important in scaling explosive-induced waves in earth materials and the effect of these waves on deep underground structures. Basically, two approaches to scaling are possible. Gravitational effects can be allowed for and material properties scaled, or gravitational effects can be ignored and material properties kept the same in the model as in the prototype. The study indicates that peak strain is dependent upon yield as well as other factors. Closure distances resulting from confined detonations vary from 1.85 to 2.00 ft/lb$^{1/3}$, the variation apparently being due to properties of rock. The strain magnitude times the strain pulse period together with the energy level of the pulse appear to be reliable parameters for damage prediction. High explosives (HE) and unclear explosives (NE) are believed to be almost equal in effect for depths of burial greater than $\lambda_c = 0.20$ ft/lb$^{1/3}$; for shallower burial, an equivalence factor must be used. (U)

(U) The foregoing analysis indicates that model scaling can be used to advantage to investigate a number of the factors which are important in the response of deep underground structures to explosive attack. (U)

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INFORMATION

U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION
CORPS OF ENGINEERS
OFFICE OF THE DIRECTOR
VICKSBURG, MISSISSIPPI 39181

REFER TO

AD-368244

ERRATA SHEET 12 January 1966

Technical Report No. 1-695

SOME BASIC PRINCIPLES OF SCALING
EXPLOSION-PRODUCED DAMAGE TO
DEEP UNLINED OPENINGS IN ROCK (U)

October 1965

Please delete the following from the cover and title page, and from paragraph 12 of DD Form 1473 at end of report:

"Research and Development Command, U. S. Army
and"

Defense Threat Reduction Agency
45045 Aviation Drive
Dulles, VA 20166-7517

CPWS/TRC March 26,1999

MEMORANDUM TO DEFENSE TECHNICAL INFORMATION CENTER
ATTN: OCQ: MR WILLIAM BUSH

SUBJECT: DOCUMENT REVIEW

The Defense Threat Reduction Agency's Security Office has reviewed and declassified the following documents:

USNRDL-TR-133, AD-145694, UNCLASSIFIED, STATEMENT A
URS-B162-6, AD-349217, UNCLASSIFIED, STATEMENT D, ADMINISTRATIVE OR OPERATIONAL USE, 3/19/99
USNRDL-TR-215, AD-C006187, UNCLASSIFIED, STATEMENT A
URS-162-8, AD-348723, UNCLASSIFIED, STATEMENT D, ADMINISTRATIVE OR OPERATIONAL USE, 3/19/99
WES-TR-2-471, AD-909045, UNCLASSIFIED, STATEMENT C, TEST AND EVALUATION, 3/9/72.
WES-TR-1-695, AD-368244, UNCLASSIFIED, STATEMENT A
WES-MP-1-689, AD-356460, UNCLASSIFIED, STATEMENT C, ADMINISTRATIVE OR OPERATIONAL USE, 3/23/99

These documents were reviewed under the Executive Order 12958.

Ardith Jarrett

ARDITH JARRETT
Chief, Technical Resource Center

Completed
7 Jun 2000
B.W.